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Research paper

How water amounts and management options drive Irrigation Water Productivity of rice. A multivariate analysis based on field experiment data

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ABSTRACT

Rice cultivation is globally hampered by several conditions, which urge farmers to maintain adequate production levels while properly managing irrigation water. This has noticeable repercussions on the efficient use of the resource and on water productivity. Nonetheless, more often, this latter topic is addressed by estimating the respective values, without deeply investigating the possible causes behind such discrepancies. The main objective of this paper is to overcome such limitations, by (i) providing a comprehensive and updated overview of Irrigation Water Productivity (IWP) for rice, and (ii) exploring the role of irrigation water in determining IWP value. The analysis of experimental data collected from 51 studies reveals IWP to vary between 0.09 and 8.10 kg m^{-3}, with mean and median values of 1.36 and 0.85 kg m^{-3} respectively; moreover, a non-linear relationship between irrigation water amounts and IWP ($r^2 = 0.81$) is depicted. Further on, data are analyzed using an econometric approach. Specifically, a multivariate linear regression model is used to shed light on the joint contribution of water inputs, regime and irrigation method to productivity. This demonstrates the significant roles of irrigation ($\beta = -1.006$) and rainfall ($\beta = 0.062$) amounts, while aerobic regime and irrigation method is proved to be a further key driver ($\beta = -0.305$). Such results enable identifying the elements to be enforced, if increasing IWP for rice is the prime objective. Finally, some implications are derived for water policy and the connections with weather-climatic and environmental conditions that are globally affecting the availability of water in agriculture.

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1. Introduction

With more than 162 Million hectares cultivated worldwide (FAOSTAT, 2014), rice is one of the leading food crops, and rice-farming a strategic activity for several countries. Rice-based farming systems are particularly relevant for the rural poor in Asia, Latin America and Africa, where agriculture has a prominent subsistence role. There, it contributes in ensuring food sustenance (Mancosu et al., 2015), fostering local development and economic livelihood for farmers (FAO, 2004), preventing social unrest driven by volatility of commodity prices (IRRI, 2013). In many parts of the world, rice-farming is characterized by a marked specialization, which makes the relevant sector highly competitive and profitable. In this case, most of the final product is oriented to global markets and commercialized via international trade. In these areas, the economic importance of the sector can be substantial, so as its contribution to the economic viability. Furthermore, rice cultivation provides many ecosystem services (Matsuno et al., 2006), used as evidences of the advisability to preserve the activity. Amongst others, the environmental value of submerged paddy fields (Yoon, 2009), the creation of wetland habitats and protected areas (Natuhara, 2013), the aesthetic quality of traditional landscapes (Jung and Ryu, 2015).

At the same time, manifold conditions globally hamper the rice sector, affecting both production and competitiveness of rice-farming. For instance, the volatility of paddy rice prices (FAO, 2016) may not compensate for production costs (Ferrero and Nguyen, 2004), while in some Countries, where rice is a heavily protected good, it often faces smuggling problems (Golub, 2012). However, major concerns are mostly related to water resource, both in terms of quantity and quality. In the first instance, they arise as a problem of water availability. Shortcomings due to climate-induced effects (Olesen et al., 2011) have determined the occurrence of hot-spots of water scarcity in several areas (Bouman et al., 2007), further exacerbated by recurring and intensive droughts events. This preponderantly influences the possibility of an adequate resource

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allocation amongst sectors (Elliot et al., 2014), users and even crops within the same production pattern (Bischetti et al., 2014). In addition, even if not quantitatively limited, irrigation water may suffer from a deteriorated quality. Soil salinization and resource pollution in general may lead to a lower usability and a scarcer rice production (Clermont-Dauphin et al., 2010; Isquierdo Fraga et al., 2010). This array of conditions urges rice-farming to maintain adequate production levels, while properly managing production factors. Consequently, an optimal and rational use of the resource becomes a prime objective, possibly encouraged and sustained by water policies operating at regional or supra-national level (e.g. European Water Framework Directive). From this point of view, the adoption of water saving techniques is increasingly stimulated to mitigate the effects of climate change or to release water that would allow expanding cultivated areas.

Crop yield tends to be proportionally affected by the amount of irrigation water received (Maeda et al., 2011) and farmers' decisions should properly balance between yield and resource use (Monaco et al., 2016). In this perspective, several authors rely on the concept of "water productivity" (Molden, 1997) to assess the success of different cultivation practices (e.g., Brauman et al., 2013; Lenton, 2013; Molden et al., 2010). Though, the productivity-based approach simplifies real conditions and doesn't embark a large set of stochastic events, risks and random shocks beyond farmers' control. Additionally, it fails in providing adequate information about the use of resources. For these reasons, water productivity as a sole indicator conveys too limited information and does not allow to deduce helpful insights on the efficient, rational, optimal use of irrigation water (Seckler et al., 2003). Quoting from Wichelns (2015), likewise, estimations of productivity and yields over time and locations inadequately indicate desirable changes, either in water management practices or in production results. The author also recognizes that most of the studies only estimate water productivity, without discussing the plausible causes behind the observed discrepancies amongst values. According to a FAO survey (FAO, 2003), water productivity in agriculture strongly augmented in the period 1961–2001, mostly thanks to yield increase. In rice-farming, this is even exacerbated in recent times, by the time the sector has been experiencing the introduction of short-cycle, high yielding cultivars and ameliorated varieties (e.g., Clément and Louvel, 2013) suitable for the cultivation under limited water supplies. The "more crop per drop" paradigm (Kijne et al., 2003) may benefit from such innovations (Ben Hassen et al., 2016), which contribute to stabilize or increase grain yield. On the other hand, Zwart and Bastiaanssen (2004) ascribe variability of water productivity also to climate conditions; indeed Irrigation Water Productivity for rice was estimated during both the rainy season (e.g., Sarkar et al., 2002; Pandey et al., 1989; Islam et al., 1986), and summer (e.g., Uppal et al., 1991; Hassan et al., 1989; Marimuthu and Lulandaivelu, 1987; Islam et al., 1986). It must also be recognized that irrigation water management is a further source of variability, but scarce evidences about this are provided.

Starting from these considerations, the study at hand aims at deepening how water inputs and irrigation strategies drive productivity of rice. To our best knowledge, a comprehensive and updated overview of its productivity values is still missing. The only study addressing to this topic was carried out by Zwart and Bastiaanssen (2004), who reviewed crop water productivity for rice and other irrigated crops. This analysis could rely upon a small number of publications and trials and was limited to highlight the variation of productivity with respect to individual independent variables. The main objective of our analysis is to overcome such limitations, exploring the role of irrigation water in determining productivity. An extensive literature review was carried out to collect a large set of published experimental data. Afterwards, the analysis was conceived on an econometric basis; specifically, a multivariate linear regression model was used to shed light on the joint contribution of water inputs (i.e., supplied amounts), regime and irrigation method to productivity. The next section introduces both conceptual and methodological approach, then results are presented and discussed. Finally, some insights to address irrigation water policies are derived.

2. Conceptual and methodological approach

2.1. Irrigation water productivity

Traditionally, rice cultivation requires the use of a large amount of water. Irrigation water might account for most of the resource used at farm-level, despite in some cases it might be small (Barker et al., 2003). This is even more valid for arid and semi-arid regions, where agriculture is mostly or fully dependent on irrigation. Besides, farmers can directly intervene on irrigation volume. Whereas facilitate and affordable access to water is at farmers' disposal, they generally have large influence and control over water volumes, timing and supply (Wichelns, 2015). Irrigation water is thus a key element for rice-cultivation practices; for this reason, water productivity is hereinafter referred to as Irrigation Water Productivity (IWP, kg m^{-3})

$$IWP = 100 * \frac{P}{I} \quad (1)$$

where P is the paddy rice yield (t ha^{-1}) and I the seasonal irrigation water volume (mm).

2.2. Data sourcing and collection criteria

A review of international literature of the last twenty years was carried out to select a substantial number of studies concerning (i) the use of water inputs on rice as the sole crop, and (ii) their respective production performances. It was aimed at collecting data and information from field experiments performed worldwide. During this time-span – though the development of new practices and the improvement in the use of production factors – no marked modifications in the rice-production system occurred. Consequently, the influence of new techniques on the rice sector can be considered minimal, and the conditions of the production sector quite stable.

A large dataset was created based on experimental data from studies that provided some precise information. Only measured values were considered, while results from water balance simulations and yield-predictive models were excluded. Papers should (i) indicate the precipitation amount occurred at the experimental site during the growing season, (ii) report minimally two data between Irrigation Water Productivity, yield and irrigation amounts and (iii) clearly indicate how irrigation water was administered. Each value was considered individually, while average values – per experimental year or management strategy applied – were not included in the data set.

A great variability in locations (climate and soil type implications), agronomic choices (e.g., fertilization rates, rice cultivars) and water use was noticed. Such a complexity reflects the heterogeneity of agricultural practices and the possible combinations of production factors that may be adopted at farm-level (Zwart and Bastiaanssen, 2004). Similarly, a large array of irrigation strategies was found. To facilitate the subsequent analyses and explore their contribution to the variability of IWP, such strategies were firstly grouped under the water regime performed, i.e., flooding irrigation or aerobic rice, and then further differentiated on the basis of irrigation method and water management (Table 1).

Table 1
Water regime and management options reviewed from literature, as grouped and considered for the subsequent analyses.

Water regime	Irrigation strategy and method	
Flooding irrigation	(I) Continuous flooding	Paddy field remains submerged for the largest part of the rice-growing period, except for brief periods to allow fertilizations or herbicide treatments. Water is applied either immediately after tillage operations, or after soil-seeding of rice (i.e. delayed application).
	(II) Intermittent flooding	No permanent water depth is maintained on rice field; rather, alternately submersions and drying periods occur during the whole growing season (e.g., Alternate Wetting and Drying, System of Rice Intensification, semi-dry cultivation)
Non-flooding irrigation (aerobic rice)	(III) Unspecified irrigation method	No water layer is maintained on the field, irrigations are applied periodically or whenever needed (i.e., at the appearance of soil cracking or at pre-defined soil moisture tensions). Unspecified modality of water application.
	(IV) Other irrigation methods	No water layer is maintained on the field; irrigation water is applied periodically or whenever needed by sprinkler, drip or furrow irrigation.

2.3. The regression model

A multiple linear regression model was used to investigate the main drivers of IWP. The general model is based on the formulation

$$Y = \beta X + \varepsilon \tag{2}$$

with Y the vector of observations, β the vector of regression coefficients, X the matrix of regressors and ε the vector of erratic variables.

In this study, a group of explanatory variables concern total water supply, namely the amounts of water received by rainfall and irrigation. According to (1), precipitations are not likely to directly affect water productivity. Rainfall amounts rather enter the model as proxies for climatic conditions, implicitly considering (i) the location of experimental sites and (ii) the level of water available to agriculture. At farm level, the same irrigation volume may be differently managed. In general terms, lower irrigation amounts are more frequently coupled with water saving techniques; grain yield, however, may not be particularly affected by such a condition, finally resulting in the increase of IWP. To test this hypothesis, various water management options described in Table 1 were included in the model as dummy variables. Table 2 lists all the variables considered in the model.

Accordingly, the regression model was explicitly defined in its matrix form as

$$\begin{bmatrix} IWP_1 \\ IWP_2 \\ \vdots \\ IWP_n \end{bmatrix} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \\ \beta_6 \end{bmatrix} \begin{bmatrix} 1 & R_1 & I_1 & FL_{CONT1} & FL_{INT1} & AE_{INT1} & AE_{OTH1} \\ 1 & R_2 & I_2 & FL_{CONT2} & FL_{INT2} & AE_{INT2} & AE_{OTH2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & R_n & I_r & FL_{CONTn} & FL_{INTn} & AE_{INTn} & AE_{OTHn} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \tag{3}$$

Afterwards, the relationship was made linear by adopting the logarithmic transformation of numeric variables:

$$\begin{bmatrix} \ln(IWP_1) \\ \ln(IWP_2) \\ \vdots \\ \ln(IWP_n) \end{bmatrix} = \begin{bmatrix} \beta_0^* \\ \beta_1^* \\ \beta_2^* \\ \beta_3^* \\ \beta_4^* \\ \beta_5^* \\ \beta_6^* \end{bmatrix} \begin{bmatrix} 1 & \ln(R_1) & \ln(I_1) & FL_{CONT1} & FL_{INT1} & AE_{INT1} & AE_{OTH1} \\ 1 & \ln(R_2) & \ln(I_2) & FL_{CONT2} & FL_{INT2} & AE_{INT2} & AE_{OTH2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \ln(R_n) & \ln(I_r) & FL_{CONTn} & FL_{INTn} & AE_{INTn} & AE_{OTHn} \end{bmatrix} + \begin{bmatrix} \varepsilon_1^* \\ \varepsilon_2^* \\ \vdots \\ \varepsilon_n^* \end{bmatrix} \tag{4}$$

where $\beta_\cdot^*$ and $\varepsilon_\cdot^*$ represent respectively the coefficients and the erratic variables of the regression model, not necessarily equivalent to the previous formulation (3).

3. Results

3.1. Field experiments: overview of locations and water management options

A total number of 51 publications was selected from international literature. They include either regional analyses or field experiments performed over years in 15 different countries across all the continents (Table 3). The largest part of them was carried out in Asian countries, especially India (n = 18) and China (n = 14), where almost half of the world rice-growing area is concentrated (FAOSTAT, 2014). Notwithstanding, the constraints imposed by the selection criteria did not allow finding relevant literature for a large part of South-Eastern Asia (e.g., the Lower Mekong Basin), where top rice exporter countries are located. At the same time, few studies refer to the rest of the world: only two focus on Brazil, three on Australia and few while remaining papers describe various possibilities for rice cultivation in other six Countries (see the Appendix A).

Each selected paper reports the results of several trials carried out at the same experimental site, either under different conditions or repeated in different years (see Appendix). Altogether, the performed experimentations resulted in the 556 treatments finally included in the analysis. 204 trials addressed to the continuous flooding method, while the most part tested the effects of a reduced water supply on rice quality and production. In particular, 206 treatments explored intermittent flooding. Especially in this latter case, great attention was paid to Alternate Wetting and Drying (AWD) (e.g., Shao et al., 2014; Chahal et al., 2007) and System of Rice Intensification (SRI) (e.g., Gopalakrishnan et al., 2014; Thakur

Table 2
Variables included in the multiple linear regression model.

	Variable	Type	Unit
IWP	Irrigation water productivity	Dependent	kg m^{-3}
R	Total rainfall during growing season	Independent – numerical	mm
I	Irrigation water volumes during growing season	Independent – numerical	mm
FL_{CONT}	Continuous flooding	Independent – dummy	1 if Yes, 0 otherwise
FL_{INT}	Intermittent flooding	Independent – dummy	1 if Yes, 0 otherwise
AE_{INT}	Aerobic rice, unspecified irrigation method	Independent – dummy	1 if Yes, 0 otherwise
AE_{OTH}	Aerobic rice, specified irrigation method	Independent – dummy	1 if Yes, 0 otherwise

Table 3
Key facts of literature review.

Continent	Publications (number)	Countries (number)
Africa	2	2
Americas	4	3
Asia	41	8
Australia	3	1
Europe	1	1

et al., 2014). Periodic irrigations on non-flooded fields were mainly performed at experimental sites characterized by either temperate or tropical climates, where seasonal irrigation water volumes may be higher than 1300 mm. Intermittent irrigations based on soil water content or moisture tension (e.g., Ghosh et al., 2011; Li et al., 2007) prevailed in arid and semi-arid regions, but even in those temperate zones where drought is a limiting factor for rice production. Here, seasonal water supply rarely exceeded 600 mm, administered through furrow (Jin et al., 2016; He et al., 2013), drip (He et al., 2013) and sprinkler (Kato et al., 2009) irrigations. Such studies were conducted in more recent years, from 2009 onwards, for a total number of 29 treatments (5% of total trials).

3.2. Irrigation water amounts and productivity

Based on the analysis of the whole dataset (Table 4), it could be inferred that a precise correspondence between irrigation amounts and management options does not exist. Water volumes lower than approximately 1700 mm might, in fact, be administered through different irrigation strategies. On the contrary, higher volumes are typical of submerged paddy fields only.

Nevertheless, it is noteworthy that irrigation strategies are significantly different per water volumes applied (Table 4). This further confirms continuous flooding to be the most water-consuming practice, with an average seasonal water use of 1208 mm. This is indeed characterized by a great variability, which remarks the actual use of an even larger water supply. Other data from literature, not included in the current analysis, are particularly consistent with this latter possibility. Moreno-Jiménez et al. (2014) supplied rice fields in a Mediterranean area of Spain with 2400 mm, while seasonal water use in Lombardy region, Northern Italy, is estimated in 4020 mm (Altobelli et al., 2011); besides, IRRI estimates the use of 1300–1500 mm for irrigated rice in Asian countries. A reduced permanence of water depth, i.e., intermittent flooding instead enables to save 33% of the resource, whereas dry-land cultivation implies the use of even lower water volumes. Compared to continuous flooding, aerobic rice enables using up to 591 mm, with a water use reduction ranging from 51% to 59%. Our findings are further corroborated by other studies that refer to water saving techniques: as regards AWD, it is reported to reduce irrigation by 15–30% (Lampayan et al., 2014), while rice-cultivation under dry-land conditions potentially lowers water volumes up to 50% (Bouman et al., 2005a,b). Therefore, in general terms, decreasing irrigation water volumes can be ascribable to different irrigation modalities and managements. This also determines higher productivities. As by definition, in fact, an inversely proportional relationship links irrigation water amounts and IWP; according to our results, it is found out to be non-linear (Fig. 1a). The relationship shows a high r-squared (0.81), which demonstrates statistical significance for the entire dataset. IWP values concerning all the treatments vary between 0.09 and 8.10 kg m^{-3}, with mean and median values of 1.36 and 0.85 kg m^{-3}, respectively. Extreme values refer to different sets of experimentations conducted in Japan. In the former, Hayashi et al. (2006) indicated that under continuous flooding, irrespective of the water supply, a lower planting density negatively affected IWP, which followed a decreasing trend. Kato et al. (2009) instead focussed on yield potential of direct-seeded aerobic rice under sprinkler irrigation, compared to transplanted rice in puddled fields with a permanent water depth. Additionally, Liu et al. (2005) made a similar comparison by performing multiple mulched non-flooded trials and finally attained two of the highest IWP, 8.04 and 8.03 kg m^{-3}.

Moreover, non-linearity between IWP and I is peculiar of each water management option (Fig. 1b–e), though the significance of each relationship largely depends on the number of observations. Consequently, lower irrigation amounts are coupled with higher productivities, which finally are significantly different one another (Table 5). The main reason of this may be traced back to a stronger reduction in water volumes, rather than in yield. These latter are in fact very similar within the same water regime: continuous and intermittent flooding show average productions of 6.54 t ha^{-1} and 6.56 t ha^{-1} respectively (non-significantly different under a p-value <0.05), whereas aerobic rice yields 5.30 t ha^{-1}. In general terms, higher levels of productivity are coupled with higher yields (e.g., Jiang et al., 2016; Kato et al., 2009), or the reverse is true (Dwivedi et al., 2012; Ceesay, 2011).

3.3. Results of the multivariate analysis

Prior to multivariate regression, a correlation analysis was run to check for multicollinearity amongst explanatory variables. In most cases, correlation was found to be low, between 0.01 and 0.4 (Table 6). In first instance, it is noticeable the negative correlation between irrigation and rainfall. The irrigation period is often dependent on the occurrence of rainy events. This also supports that in arid and semi-arid regions more supplemental irrigation is needed, which balances the scarce rainfall amounts; conversely, either under a full water availability or in tropical and monsoon areas, where rainfall during the rice-growing season may be high, irrigation water volumes may be scarcer. Finally, despite the coefficient between FL_{CONT} and FL_{INT} (i.e.,|0.584|) was over the cut-off of |0.50| suggested by Hair et al. (2010), both the variables were included in the model, to not exclude *a priori* any water management strategy.

Table 7 shows the descriptive statistics relative to both the dependent and the explanatory variables.

A stepwise procedure, based on Ordinary Least Squares (OLS), was then used to run the model. Thanks to the large number of observations, it was considered robust enough as not to perform further bootstrap analyses. As shown in Table 8, the regression anal-

Table 4
Irrigation water amounts (mm) for rice under different water management options.

Water management option	Mean (mm)	Standard deviation	Min	Max
Continuous flooding	1208 a	1265	112	9970
Intermittent flooding	806 b	516	115	2470
Aerobic rice (unspecified irrigation method)	591 c	319	72	1661
Aerobic rice (specified irrigation method)	493 cd	168	100	1374

Means followed by different letters are significantly different (Tukey's post hoc test, $p < 0.05$).

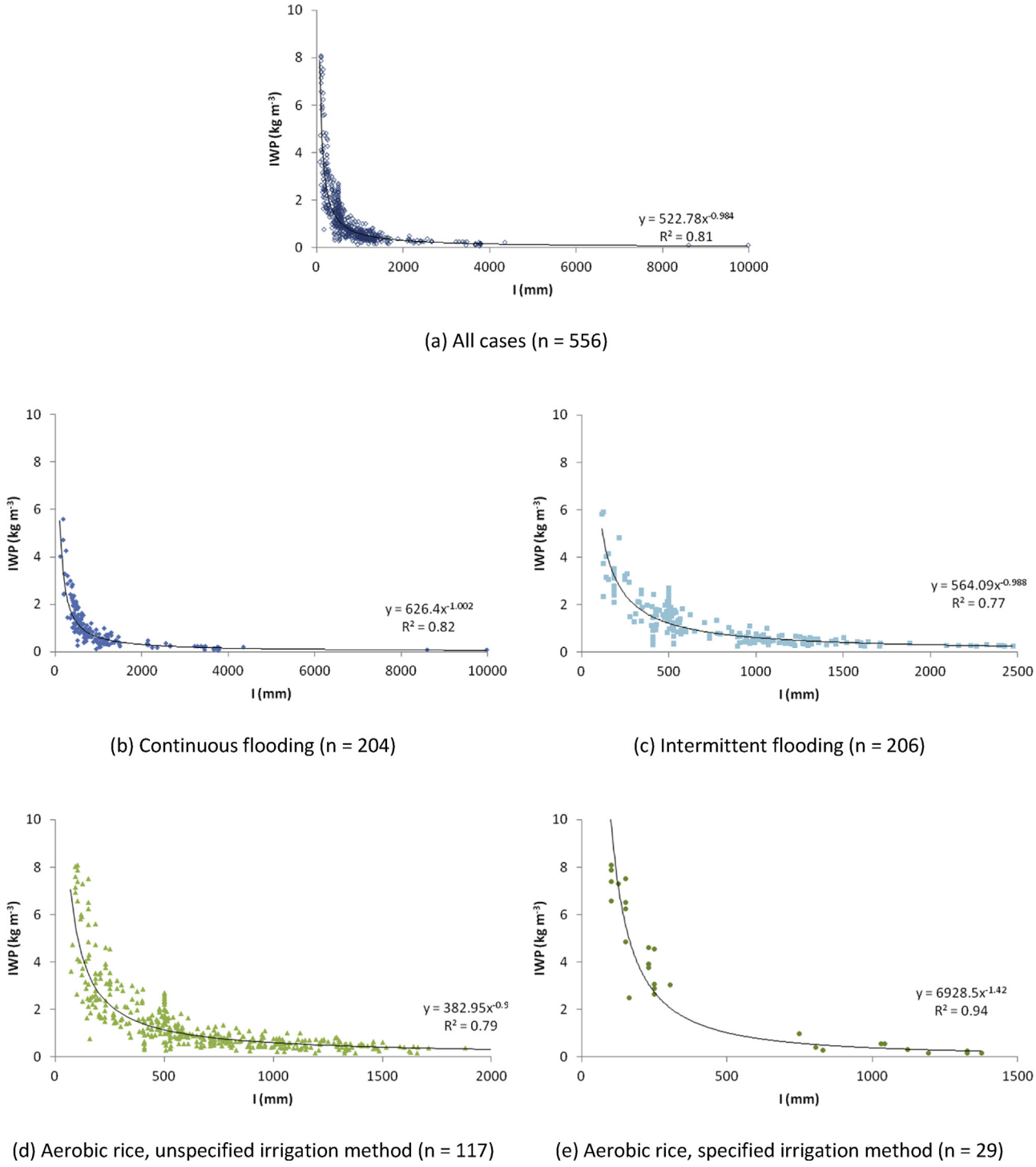
IWP (kg m-3)
I (mm)
y = 522.78x-0.984
R² = 0.81
(a) All cases (n = 556)
y = 626.4x-1.002
R² = 0.82
(b) Continuous flooding (n = 204)
y = 564.09x-0.988
R² = 0.77
(c) Intermittent flooding (n = 206)
y = 382.95x-0.9
R² = 0.79
(d) Aerobic rice, unspecified irrigation method (n = 117)
y = 6928.5x-1.42
R² = 0.94
(e) Aerobic rice, specified irrigation method (n = 29)

Fig. 1. Relationship between irrigation water amounts (I) and Irrigation Water Productivity (IWP). Note: scatter plots have different scales. See Table 1 for a complete description of irrigation strategies.

Table 5
Descriptive statistics of Irrigation Water Productivity (kg m^{-3}) under different water management options.

Water management option	Mean (kg m^{-3})	Standard deviation	Min	Max
Continuous flooding	0.99 a	0.86	0.09	5.61
Intermittent flooding	1.27 b	1.04	0.25	5.92
Aerobic rice (irrigation method unspecified)	1.67 c	1.80	0.17	8.04
Aerobic rice (irrigation method specified)	3.49 d	2.79	0.16	8.10

Means followed by different letters are significantly different (Tukey's post hoc test, $p < 0.05$).

Table 6
Correlation matrix (Pearsons' two-tailed test).

	Ln(R)	Ln(I)	FL_{CONT}	FL_{INT}	AE_{INT}	AE_{OTH}
Ln(R)	1.000					
Ln(I)	−0.209**	1.000				
FL_{CONT}	-0.010 ns	0.283**	1.000			
FL_{INT}	−0.106*	0.018 ns	−0.584**	1.000		
AE_{INT}	0.134**	−0.248**	−0.393**	−0.396**	1.000	
AE_{OTH}	0.008 ns	−0.197**	−0.179**	−0.180**	−0.120**	1.000

ns: not significant.
** $p < 0.1$.
* $p < 0.05$.

Table 7
Descriptive statistics of the variables included in the regression model.

Variable	Observations (n.)	U.m.	Range	Min	Max	Mean	Standard deviation
Ln(IWP)	556	kg m^{-3}	4.53	−2.44	2.09	−0.10	0.89
Ln(R)	556	mm	8.02	1.53	9.55	8.18	0.97
Ln(I)	556	mm	4.94	6.57	11.51	8.77	0.82
FL_{CONT}	556	–	1	0	1	0.37	0.48
FL_{INT}	556	–	1	0	1	0.37	0.48
AE_{INT}	556	–	1	0	1	0.21	0.41
AE_{OTH}	556	–	1	0	1	0.05	0.22

Table 8
Results of the stepwise OLS linear regression. Only significant regressors are shown.

Source	SS	df	MS	Number of obs = 556
Model	367.589	3	122.530	F(3552) = 918.539
Residual	73.635	552	0.133	Prob > F = 0.000
Total	441.224	555		R-squared = 0.833
				Adj R-squared = 0.832
				Root MSE = 0.365

Ln(IWP)	Coef.	Std. Err.	t	P > |t|	[95% Conf. Interval]		VIF
Constant	8.273	0.241	34.329	0.000	7.800	8.747	
Ln(I)	−1.006	0.020	−50.476	0.000	−1.045	−0.967	1.103
Ln(R)	0.062	0.016	3.790	0.000	0.030	0.095	1.074
AE_{INT}	−0.305	0.039	−7.736	0.000	−0.362	−0.227	1.054

ysis identifies three significant drivers amongst all the explanatory variables included in the model.

A systematic relationship between dependent variable and significant predictors is demonstrated by the goodness-of-fit of the model (F-test significant under *p*-value <0.01). The high adjusted r-squared suggests that they jointly contribute for more than 83% to the variability of IWP, without problems of multicollinearity, as demonstrated by the variance inflation factors (VIF). More in detail, IWP mostly depends on water inputs, with the role of irrigation largely prevalent over seasonal rainfall amounts. In general terms, it is further confirmed the relationship between IWP and irrigation, as indicated by the respective negative coefficient linking them. In this case, a unit diminution in Ln(IWP) ($\beta_2 = -1.006$) can be observed for a unit augmentation in Ln(I). Yet, results from the econometric approach go beyond the mere definition of IWP adopted, which is irrespective of precipitation amounts. The multivariate analysis instead points out its significant and positive relation with rainfall. Actually, it is not the main driver of IWP. Rather, the relationship suggests that, under the same irrigation volume, higher precipitations are coupled with a very slight increase in IWP ($\beta_3 = -0.062$). This indicates the scarcer contribution of local climate conditions to productivity: a role statistically significant, but quantitatively irrelevant. Similarly, we can hypothesize that a climate-induced reduction of rainfall amounts would not markedly affect IWP. Besides, neither water regimes, nor irrigation methods are particularly incisive in driving the variability of IWP. Each variable concerning irrigation strategy was systematically excluded by the model when running, as not respecting a significance threshold. Only the presence – or not – of aerobic rice (specifically AE_{INT}) is shown as a key driver of IWP. In particular, the coefficient of the relevant dummy variable ($\beta_6 = -0.305$) indicates its diminution if aerobic cultivation is performed.

It must be pointed out that such relationship doesn't properly indicate the cause-and-effect nexus operated by the regressors on the dependent variable; rather, the effects of each independent variable arise all others being equal. Given the initial assumptions of this study, IWP better depicts partial factor productivity (Barker et al., 2003), rather than total factor productivity. Indeed, paddy

rice production relies upon multiple other inputs, not explored here; for this reason, the regression equation returned by the model may be interpreted as a partial production function, where only water-related aspects explain grain yield:

$$\ln(Y)_n = 8.273 + 0.062\ln(R)_n - 0.006\ln(I)_n - 0.305AE_{OTHn} + \varepsilon_n \qquad \forall n \quad (5)$$

In this case, the main driver can be traced back to irrigation strategy, followed by rainfall amounts (i.e., climate conditions and locations) and, lastly, by irrigation water volumes. Yield does not undergo any change following a unit variation in irrigation amounts, since the respective elasticity coefficient is proximate to zero (−0.006). At the same time, all the determinants of yield and other stochastic effects can be summarized by the error term ε.

4. Discussion

Data collected from literature review have served as a characterization of production system in several rice-producing areas, and especially where – Africa, Americas and Australia – studies concerning productivity are scarcely addressed. Different studies focussing on water consumption and irrigation efficiency refer to very diverse agro-systems. In many areas of the world, agronomic practices in rice cultivation provide the tillage of submerged soil before sowing to disrupt soil structure (i.e., puddling). These operations determine a more compact soil, with lower percolation losses and increased irrigation efficiency and water productivity. The situation is very different in southern Europe, where puddling is not practiced and data on water consumption, irrigation efficiency and productivity are very scant. In this regard, Sánchez-Llerena et al. (2016) estimated that IWP in Extremadura, Spain, is around 0.61 kg m^{-3}. This shows some similarities with the evidences provided in this paper (see the Appendix), which indicates IWP for Northern Italian rice ranging between 0.11 and 0.67 kg m^{-3}.

Nonetheless, considerations about IWP overview are extremely indicative: lower and upper bounds of IWP are still subject to variation, given the possibility to widen the case record with further experimental data. Besides, our analysis considered field experiments performed in the last 30 years. Therefore, advanced practices in experimental conditions would strongly affect the possibility of a reasonable comparison within a vast set of data. Repeating a similar study in the next future taking into consideration either a shorter or a more recent time-span will possibly lead to different results. As another concern, it must be recognized that field experiments are usually performed under optimal and controlled conditions, which might not be ensured at farm or regional level. A wide heterogeneity in agro-climatic parameters and resource use, as well as complex dynamics that operate at a larger scale, makes difficultly feasible the adoption and the spreading of the same cultivation practices. For this reason, research should embark more efforts in deepening the possibility to scale-up trials and their respective results.

The relationship between IWP and irrigation water shows how, despite very dissimilar observations for experimental conditions and designs, overall depicts a significant common trait, where no outliers are evident. Likely, the heterogeneity in locations and practices has a minor role in determining the general trend of IWP. The identified trend can be considered explanatory of general behaviour also thanks to the large number of observations, which enforces its robustness and makes considerations reasonable. It founds confirmation in the neoclassical macroeconomic theory (Mitscherlich, 1925) or, similarly, in the Liebig's law of the minimum (Sprengel, 1839), more popular among the agronomists. Consequently, the more irrigation water is used, the more marginal grain yield decreases, until when it becomes negative and an additional unit of water input causes an output reduction. In flooded paddy fields, the large amount of water supplied is not used to sustain physiological crop needs, but rather is due to agronomic reasons that exploit rice adaptability to submerged soils. This is somehow confirmed by the alternative formulation of the regression model (Eq. (5)), which attests gross irrigation amounts to be a minor, though significant, driver of grain yield. Notwithstanding other conditions, yield potentially remains constant at varying administered water volumes. No remarkable quantitative differences are observed by shifting from continuous to alternate flooding. By contrast, yield of aerobic rice is significantly lower, owing to higher environmental stresses the crop is subject to and other implications of dry-land conditions. In this perspective, trade-offs between reduced yields and increased IWP should be also economically accounted, for instance by quantifying Economic Water Productivity (Ben Hassen et al., 2016; Pereira et al., 2012), before recommending water saving strategies.

Outputs from the regression model enable identifying the elements to be enforced, and possibly how to do so, if increasing IWP is the prime objective. *Ceteris paribus*, irrigation amounts more affect IWP. In this case, we can hypothesize that a reduction in supplied water as well as incentives for a more rational use should be encouraged. These could be quite easily achieved by charging farmers with a fixed fee per unit of water delivered (e.g., Garrido and Llamas, 2009). Water supply tariff is largely proved to be a key factor in determining the amount of water to be used by irrigated agriculture (Bartolini et al., 2007; Dono et al., 2006; Gomez-Limon and Riesgo, 2004), favouring a more effective allocation, driving the switch to cultivation of less-water demanding crops or determining the exploitation of other water sources. Under the practice of water saving techniques, farmers might benefit from a reduction of rice production costs, and a possible increase of their revenues (Monaco et al., 2016); on the other hand, a strong reduction of water availability may lead to a profound modification of the production pattern. Actually, one of the main objective of farmers is maintaining an adequate economic return, which more often benefits from the application of a fixed fee per hectare of irrigated land (e.g., as applied by Water Users Associations in Northern Italy, or in California) and is thus conflicting with water saving. A variable crop-based charge may be a valid compromise solution between the two options. The type and the amount of irrigation rate, when applicable, are elements that policy makers should handle carefully; they in fact should not be implemented indiscriminately, but rather adapted to each different context. In addition, though not always aligning with the achievement of a high agricultural productivity, formal water markets (Palomo-Hierro et al., 2015) show potentialities to counteract climate change-induced negative impacts, as well as improve the efficiency of water use (Easter et al., 1999). Like other policy and pricing options, they however may lead to scarce environmental and equity benefits: only a proper implementation ensures they role in supporting decisions at different levels. It is of upmost importance to develop site-specific actions in order to improve the intrinsic conditions of each production system. For instance, the comparison of the performance of Italian rice-farming with the similar production structures of California and Australia calls for agronomic interventions to enhance production potential of available varieties. In this perspective, the re-allocation of either water amongst conflicting uses or irrigation water amongst farmers should be carefully considered.

5. Conclusions

This study contributes to fill the gap in exploring the variability of Irrigation Water Productivity for rice. It first explores its numerical variability, based on an extensive collection of measured data from international literature. Accordingly, the approach provides an overview of the IWP values. Such an indicator is not reliable enough to reflect a rational or effective management of

water resource; consequently, IWP issue assumes the connotation of a typical "wicked problem" that allows to specify only if an experimental condition performs better or worse than others. However, drawing similar conclusions for data presented in this paper appears quite risky, since they result from very different farming practices and site-specific conditions. In this sense, factors related to water use and management confirmed (i) the inverse relationship between IWP and irrigation volumes and (ii) the non-linear trend, consistent with the economic theory of production function. This trend characterizes both the whole set of data and the different paddy fields administrations. With reference to this last point, IWP values are statistically different, owing to progressive water savings of the distributed resource. Repetitions of these calculations including further data are needed in order to confirm – or not – findings and evidences.

The regression analysis investigates the joint variability of IWP according to water supplies and their management on the field. This approach, although limited to a small array of inputs in crop production, easily allows to draw some considerations on water policy and its potential effects on the production system, as well as the connections with weather-climatic and environmental conditions that are impacting at global level the effective availability of water for agriculture. The model identified appears sufficiently robust to be also used in a predictive sense, indicating the extent to which a modification in the explanatory variables may affect IWP. It emerges therefore the possibility of interpreting the results obtained to drive either farm-level decisions or decision-makers' interventions. To this end, it is valuable to consider the chance to run the same approach on smaller groups of data sets (e.g., per country or per region), to obtain more detailed and precise information accordingly to one or more specific purposes set up from time to time.

Appendix A. Irrigation Water Productivity values in selected papers

Location	IWP range (kg m^{-3})	Total trials (n.)	Experimental year(s)	Reference
	Flooded rice			
Continuous flooding				
Tuanlin, China	1.06–2.10	7	1999–2000	Belder et al. (2004)
Muñoz, Philippines	0.86–1.41	3	2001	Belder et al. (2004)
Millaroo, Australia	0.71–1.04	6	1989–1990	Borrell et al. (1997)
Los Baños, Philippines	0.26–0.95	19	2001–2003	Bouman et al. (2005b)
Ludhiana, India	0.14–0.41	15	2007–2008	Brar et al. (2012)
Muda Irrigation Scheme, Malaysia	0.62–1.48	3	1988–1994	Cabangon et al. (2002)
Sapu, Gambia	0.24	1	2001–2002	Ceesay (2011)
Castello d'Agogna, Italy	0.11–0.27	4	2012–2013	Cesari de Maria et al. (2017)
New Delhi, India	0.38–0.41	4	2001–2003	Choudhury et al. (2007)
Zhanghe, China	1.20–4.28	10	1991–2000	Dong et al. (2001)
Yanco, Australia	0.65–0.85	2	2008–2009	Dunn and Gaydon (2011)
Cuttack, India	0.19–0.21	2	2003–2004	Ghosh et al. (2011)
Najaf, Iraq	0.11	1	2009	Hameed et al. (2011)
Nishitokyo, Japan	0.09–0.21	13	2001–2003	Hayashi et al. (2006)
Xinjiang, China	0.26–0.28	3	2011–2012	He et al. (2013)
Murrumbridge Valley, Australia	0.72	1	n/a	Humpreys et al. (2006)
Dajin Town, China	1.91–5.61	12	2014–2015	Jiang et al. (2016)
Shiyan, China	1.03	1	2013–2014	Jin et al. (2016)
Two locations, Japan	0.26–2.87	44	2007–2008	Kato et al. (2009)
Pingtung County, Taiwan	0.68–1.43	4	2013	Kima et al. (2015)
Ndiaye, Senegal	0.61–1.24	3	2007–2009	Krupnik et al. (2012)
Two locations, Philippines	0.76–4.04	9	2009–2010	Lampayan et al. (2015a)
Muñoz, Philippines	0.5	1	2010–2011	Lampayan et al. (2015b)
Five locations, China	0.87–0.97	5	2001	Li et al. (2007)
Guangzhou, China	1.03–3.31	3	2014	Liang et al. (2016)
Chengdu plain, China	0.76	1	2001–2002	Liu et al. (2005)
Bhubaneswar, India	0.46	1	2007–2008	Mandal et al. (2013)
Gazipur, Bangladesh	0.66–0.76	2	2008–2009	Maniruzzaman et al. (2015)
Cachoeirinha county, Brazil	1.84–2.13	3	2012	Moraes Borin et al. (2016)
Zhouzhuang, China	0.92–1.65	4	2007–2008	Peng et al. (2012)
Dongbeiwang, China	0.22–0.23	2	2001–2002	Tao et al. (2006)
El Paso, Uruguay	1.01–1.61	3	2010–2013	Tarlera et al. (2015)
Mendhasal, India	0.22–0.59	10	2009–2010	Thakur et al. (2014)
Kunshan, China	0.75–0.81	2	2009–2010	Xu et al. (2013)
Intermittent flooding				
Tuanlin, China	1.33–2.63	7	1999–2000	Belder et al. (2004)
Muñoz, Philippines	0.84–1.80	6	2001	Belder et al. (2004)
Sapu, Gambia	3.06–3.23	3	2001–2002	Ceesay (2011)
Ludhiana, India	0.25–0.31	6	2004–2005	Chahal et al. (2007)
Zhanghe, China	1.59–4.84	10	1991–2000	Dong et al. (2001)
Yanco, Australia	0.53–1.11	6	2008–2009	Dunn and Gaydon (2011)
Meerut, India	0.29–0.79	27	2000–2003	Dwivedi et al. (2012)
Cuttack, India	0.26–0.39	6	2003–2004	Ghosh et al. (2011)
Patancheru, India	0.26–0.44	4	2008–2010	Gopalakrishnan et al. (2014)
Najaf, Iraq	0.29	1	2009	Hameed et al. (2011)
Two locations, Japan	0.32–4.16	28	2007–2008	Kato et al. (2009)
Ndiaye, Senegal	0.79–1.64	3	2007–2009	Krupnik et al. (2012)
Patna, India	0.77–2.14	4	2009	Laik et al. (2014)
Muñoz, Philippines	0.94–1.08	3	2010–2011	Lampayan et al. (2015b)
Guangzhou, China	1.97–5.92	4	2014	Liang et al. (2016)
Ludhiana, India	0.42–0.78	12	2006–2007	Mahajan et al. (2009)
Gazipur, Bangladesh	0.87–9.00	4	2008–2009	Maniruzzaman et al. (2015)

Two counties, MS, USA	1.98–2.70	12	2010–2012	Massey et al. (2014)
Rio Grande do Sul, Brazil	1.04–1.84	2	2010–2012	Meneghetti Sarzi Sartori et al. (2013)
New Delhi, India	0.45–0.92	3	2012	Saha et al. (2015)
Ludhiana, India	0.30–0.48	8	2009–2010	Sandhu et al. (2012)
New Delhi, India	0.34–0.60	2	2011	Shahane et al. (2015)
Southern China, China	1.46–1.77	10	2009–2010	Shao et al. (2015)
Southern China, China	1.23–1.79	10	2008–2009	Shao et al. (2014)
Ludhiana, India	0.42–0.88	8	2013–2014	Sharda et al. (2017)
New Delhi, India	0.95–1.49	4	2009–2010	Sharma et al. (2016)
El paso, Uruguay	1.25–2.00	3	2010–2013	Tarlera et al. (2015)
Mendhasal, India	0.27–0.69	10	2009–2010	Thakur et al. (2014)
	Aerobic rice			
Unspecified				
Millaroo, Australia	0.83–1.80	2	1989–1990	Borrell et al. (1997)
Various locations, China	0.77–4.75	13	2001–2003	Bouman et al. (2005a)
Los Baños, Philippines	0.43–4.13	19	2001–2003	Bouman et al. (2005b)
Castello d'Agogna, Italy	0.56–0.67	2	2012–2013	Cesari de Maria et al. (2017)
New Delhi, India	0.46–1.09	8	2001–2003	Choudhury et al. (2007)
Pantnagar, India	0.47–6.94	8	2008–2009	Dass et al. (2016)
Patancheru, India	0.32–0.79	8	2008–2010	Gopalakrishnan et al. (2014)
Nishitokyo, Japan	0.28–1.85	12	2001–2003	Hayashi et al. (2006)
Dharwad, India	1.45–2.14	4	2013–2014	Jaffar Basha et al. (2016)
Patna, India	1.13–3.56	4	2009	Laik et al. (2014)
Five locations, China	2.13–6.01	8	2001	Li et al. (2007)
Chengdu plain, China	7.17–8.04	4	2001–2002	Liu et al. (2005)
Bhubaneswar, India	0.55–0.62	3	2007–2008	Mandal et al. (2013)
Ludhiana, India	0.38–0.60	4	2013–2014	Sharma et al. (2016)
Punjab, India	0.35–3.63	8	2011–2012	Singh et al. (2016)
Dongbeiwang, China	0.17–0.58	8	2001–2002	Tao et al. (2006)
Kunshan, China	1.11–1.28	2	2009–2010	Xu et al. (2013)
Other irrigation methods				
Millaroo, Australia	0.98–2.49	2	1989–1990	Borrell et al. (1997)
Xinjiang, China	0.16–0.57	9	2011–2012	He et al. (2013)
Shiyan, China	3.03–7.30	2	2013–2014	Jin et al. (2016)
Two locations, Japan	0.26–2.87	16	2007–2008	Kato et al. (2009)
	All cases, per continent			
Africa	0.24–3.23	10		
Americas	1.01–2.70	23		
Asia	0.09–9.00	498		
Australia	0.51–4.04	19		
Europe	0.11–0.67	6		

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